Acoustical Imaging Cameras for the Inspection and Condition Assessment of Hydraulic Structures

by James A. Evans

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the initial results of an investigation to determine the feasibility of using acoustical imaging for underwater inspection of structures.

INTRODUCTION: Visibility in clear water for the human eye and optical systems such as video cameras extends to about 15 m with appropriate lighting. However, the lack of visibility caused by the presence of suspended material in some rivers and impoundments presents many mission problems for personnel of the U.S. Army Corps of Engineers. Typical situations in which lack of visibility causes problems include assessing conditions of underwater structures such as gates and concrete piers, which are Operation and Maintenance issues; positioning of float-in structures, a construction issue; the investigation of archeological sites; and detection of endangered species. Currently, condition assessments typically involve the use of divers to inspect and record the condition of underwater structural components. This is expensive and often poses the risk of personal injury to the divers.

Ultrasonic imaging system technology originally developed for the medical field helps provide potential solutions to the problems of poor visibility in turbid water. The U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg purchased an acoustical camera to evaluate and further develop its capability as a tool to aid in the inspection of structures in turbid water.

HARDWARE: Significant advances in the use of acoustical imaging systems have been made in the last several years. These systems are similar to the ultrasonic systems that have been utilized in medical applications for several decades, with the exception that a significant down-range capability is required for acoustical imaging systems. The downrange is the distance forward the camera can "see," illustrated in Figure 1. It is controlled primarily by the power transmitted by the camera. These cameras, also known as forward-looking sonars (FLS), use a variety of design approaches. The most common approaches employ line arrays, cylindrical arrays, conformal arrays, and multiple fixed beam elements. Beams are formed by mechanical means (stepper motors), electronically (analog delay lines), digital delay lines, and acoustical lenses.

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R_d Max @ 1.8 MHz = 15 m

R_d Max @ 1 MHz = 40 m

@ 1.8 MHz

Beam Height= 1/4 x R_d

Cross-Range Beam Width = ½ x R_d

Cross-Range Resolution = R_d / 96
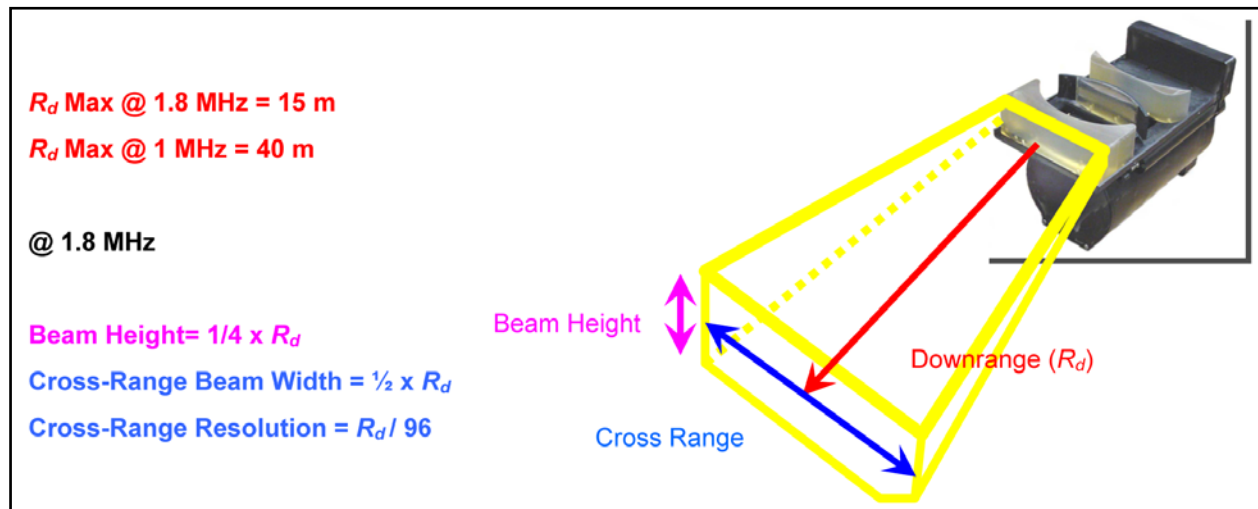
Beam Height

Downrange (R_d)

Cross Range

Figure 1. Rules of thumb on DIDSON images.

The camera ERDC purchased is a Dual Frequency Identification Sonar (DIDSON), shown in Figure 2. The camera was designed and developed by the Applied Physics Laboratory at the University of Washington in Seattle. The DIDSON uses a set of thin acoustic lenses made of polymethylpentene that focus sound on a 1-3 composite linear array (Figure 3). Acoustical lenses have several advantages over other beam-forming methods: this method is able to form any number of beams in parallel at the speed at which sound passes through the lenses; digitations occur after the beams are formed and thus require a much lower sampling rate; beam-forming takes no power; and the camera transmits and receives narrow beams through the same lens.
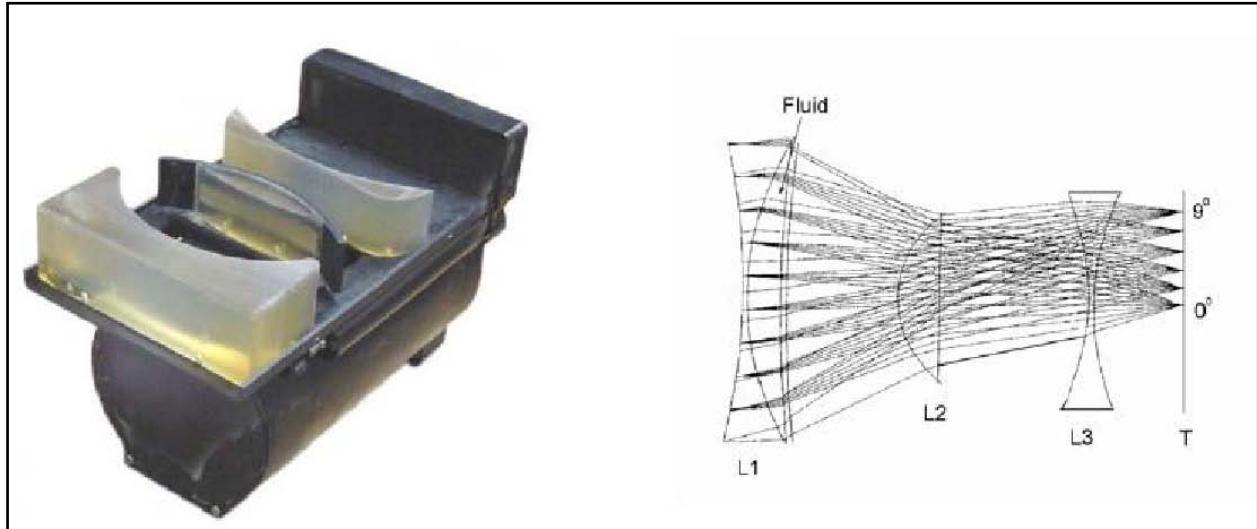

Figure 2. Dual Frequency Identification Sonar (DIDSON).

Figure 3. DIDSON camera with beamforming lens exposed and the geometry of the rays shown.

PUBLISHED DIDSON CAMERA SPECIFICATIONS, DIDSON-S (STANDARD VERSION)

Low-Frequency Detection Mode:

- Operating Frequency: 1.1 MHz (1.0 MHz < SN16)

- Beamwidth (two-way): 0.4° H by 12° V

- Number of beams: 48

- Source Level (average): 202 dB ref 1 μPa at 1 m

- Standard Range settings

  - Window start range length, m: 0.75 to 23.25 in 0.75-m intervals

  - Window length, m: 4.5, 9, 18, 36

  - Range bin size, mm, relative to window length: 8, 17, 35, 70

  - Pulse length, μs, relative to window length: 16, 32, 64, 128

- Extended Range settings:

  - Window start range length, m: 0.84 to 26.04 in 0.84-m intervals

  - Window length, m: 5, 10, 20, 40

  - Range bin size, mm, relative to window length: 10, 20, 40, 80

  - Pulse length, μs, relative to window length: 18, 36, 72, 144

High-Frequency Identification Mode:

- Operating Frequency: 1.8 MHz

- Beamwidth (two-way): 0.3° H by 12 ° V

- Number of beams: 96

- Source Level (average): 206 dB ref 1 μPa at 1 m

- Standard Range settings

  o Window start range length, m: 0.38 to 11.63 in 0.38-m intervals

  o Window length, m: 1.13, 2.25, 4.5, 9

  o Range bin size, mm, relative to window length: 2.2, 4.4, 9, 18

  o Pulse length, μs, relative to window length: 4, 8, 16, 32

- Extended Range settings

  o Window start range length, m: 0.42 to 13.02 in 0.42-m intervals

  o Range bin size relative to window length: 1.25 m, 2.5 m, 5 m, 10 m, 2.5 mm, 5 mm, 10 mm, 20 mm

  o Pulse length, μs, relative to window length: 4.5, 9, 18, 36

DISPLAY PRESENTATION: As shown in these specifications, DIDSON operates at two frequencies, selectable by the operator or automatically by the downrange requirement. The maximum downrange is 40 m, which is realized at the low detection frequency of 1 MHz. At 1 MHz, DIDSON forms 48 fan beams 0.6 degree horizontal by 12 degrees vertical spaced 0.6 degree in the horizontal direction.

At the higher identification frequency (1.8 MHz), DIDSON forms 96 beams 0.3 degree horizontal by 12 degrees vertical spaced 0.3 degree apart. DIDSON's downrange capability at this frequency is 15 m.

DIDSON has a field of view of 29 degrees at both frequencies and can focus on objects that range from 1 m to 40 m from the camera. It consumes 30 watts and measures 31 cm by 21 cm by 17 cm. The standard DIDSON acquires about 50 kB per frame, and frame rates can go as high as 20 frames per minute. Since DIDSON is a forward-looking acoustical camera with a single-line linear piezoelectric array, the selection of a grazing angle determines the display of an image (Figure 4).
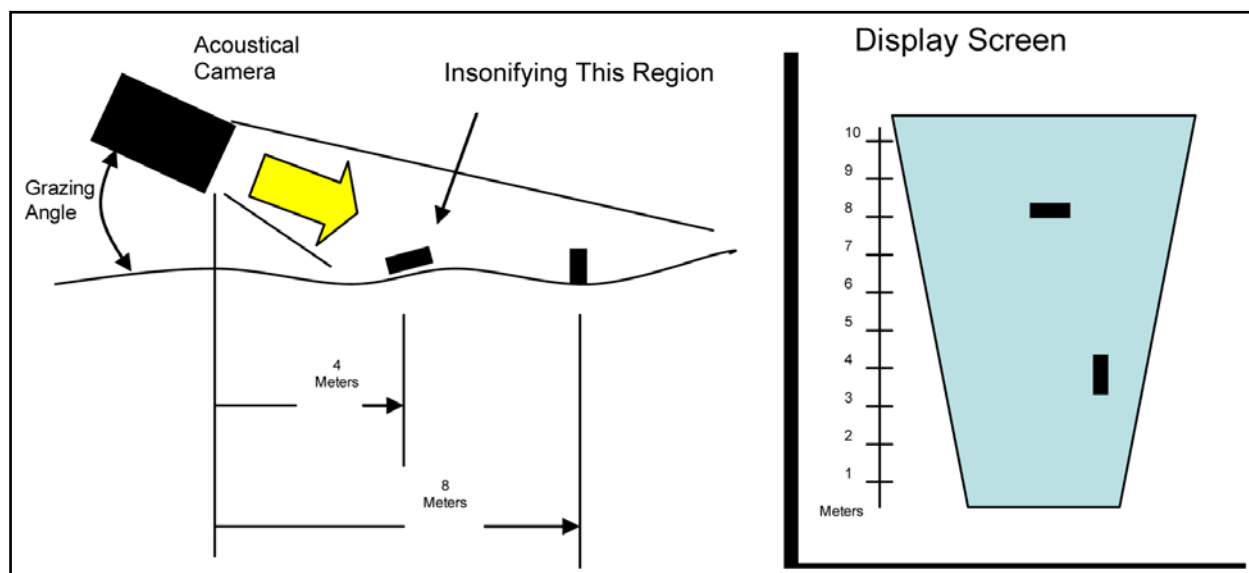
Figure 4. Relationship between position of objects and location on display.

DIDSON BEAM WIDTH AND RESOLUTION: In high-frequency mode, 1.8 MHz, each beam is 0.3 degree in the horizontal and 14 degrees in elevation. There are 96 side-by-side beams spanning a total of 28.8 degrees in the horizontal direction. The cross range of the field of view varies with downrange distance. It is approximately half the downrange distance. For example, at 10-m downrange, the cross-range field of view is 10/2 or 5 m. The beam width of each beam at this cross range is 500/96 or approximately 5 cm.

The height of each beam is approximately 0.25 times the downrange distance. Thus, 10 m out the height would be 2.5 m. Each beam would be approximately 5 cm wide and 250 cm high at 3 decibel points.

The downrange resolution is the selected window length divided by 500. For example, to view at the 2.5-m window length, the downrange resolution would be 250/500=0.5 cm (500, or more accurately 512, is the number of samples within the window).

SAMPLING TECHNIQUE: DIDSON simultaneously transmits on and then receives from sets of 12 beams. Images or frames are built in sequences of these sets. The 1.1-MHz mode uses four sets to build an image with 48 beams 0.6 degree apart from one another in the horizontal plane. The 1.8-MHz mode uses eight sets to build an image with 96 beams 0.3 degree apart from one another in the horizontal plane.

Each beam is sampled at rates from 333 kHz to 41 kHz (1.8-MHz mode) or from 83 kHz to 10 kHz (1.0-MHz mode). This gives downrange resolutions from 2.2 mm to 17.6 mm (1.8-MHz mode) or from 8 mm to 70 mm (1.0-MHz mode).

The sampled data are logs of the amplified and filtered return envelopes and vary from 0 to 255 machine units (one byte). A byte represents the return amplitude range from 0 to 90 db with 0.35-db resolution. Receiver saturation is calibrated to be at 90 db.

The data arrays formed in the 1.8-MHz mode are byte arrays 96 by 512 in size and 48 by 512 in the 1.0-MHz mode.

DIDSON SOFTWARE: The minimum computer system required for connection to the DIDSON camera is Windows XP, 2 GHz, with 512 MB of memory, a 1024 × 768 pixel display, and an Ethernet port. The DIDSON camera hardware interfaces with an Ethernet network and is fully operational when received. Communications are TCP/IP using UDP (Unsigned Datagram Protocol). The packets are always UDP protocol. The didson.ini file set up by the topside software gives the option of using a broadcast IP address for the communications. The image data may be transferred either within low-frequency (1.0 MHz) or high-frequency (1.8 MHz) large packets called frames, or by twenty-five 1024-byte (1.0 MHz) packets. This option enables the DIDSON to be supported by routers or media converters. Each frame is 25 KB (1.0 MHz) or 49 KB (1.8 MHz) of data. The maximum frame rate is limited by the bandwidth of the Ethernet connection, and the minimum frame rate is 1 per second.

The DIDSON topside software provides the following capabilities:

- Real-time display of the sonar images and associated settings
- Ability to change settings
- Recording of images
- Playback of recorded images
- Processing of recorded images.

User-changeable settings are the Frame Rate, the Receiver Gain, the Window Start (distance from the camera to begin display), the Window Length (amount of information to display), and the Focus distance. The sonar can also be changed from auto-focus and auto-gain operation to manual setting of these parameters. See Figure 5 for a display of the user interface screen.

Single frames (snapshots) and multiple frame videos can also be recorded. Both are recorded as .ddf (DIDSON Data Format) files.

Processing capabilities include the following:

- Conversion from .ddf files to .avi and .jpg formats
- Fish counting
- Marking of objects.

The software can interface with compatible GPS units to display position and velocity information. Sonar depth, pitch, and roll information can be displayed as well.

The DIDSON application maintains a header file located in the default working directory. Among the parameters saved in this header file are Frame Rate; Total Frames; Receiver Gain; Window Start; Window Length; Frequency; and Time.

Third-party applications may use these parameters to create a database of close-range bathymetry data or to provide additional data processing.
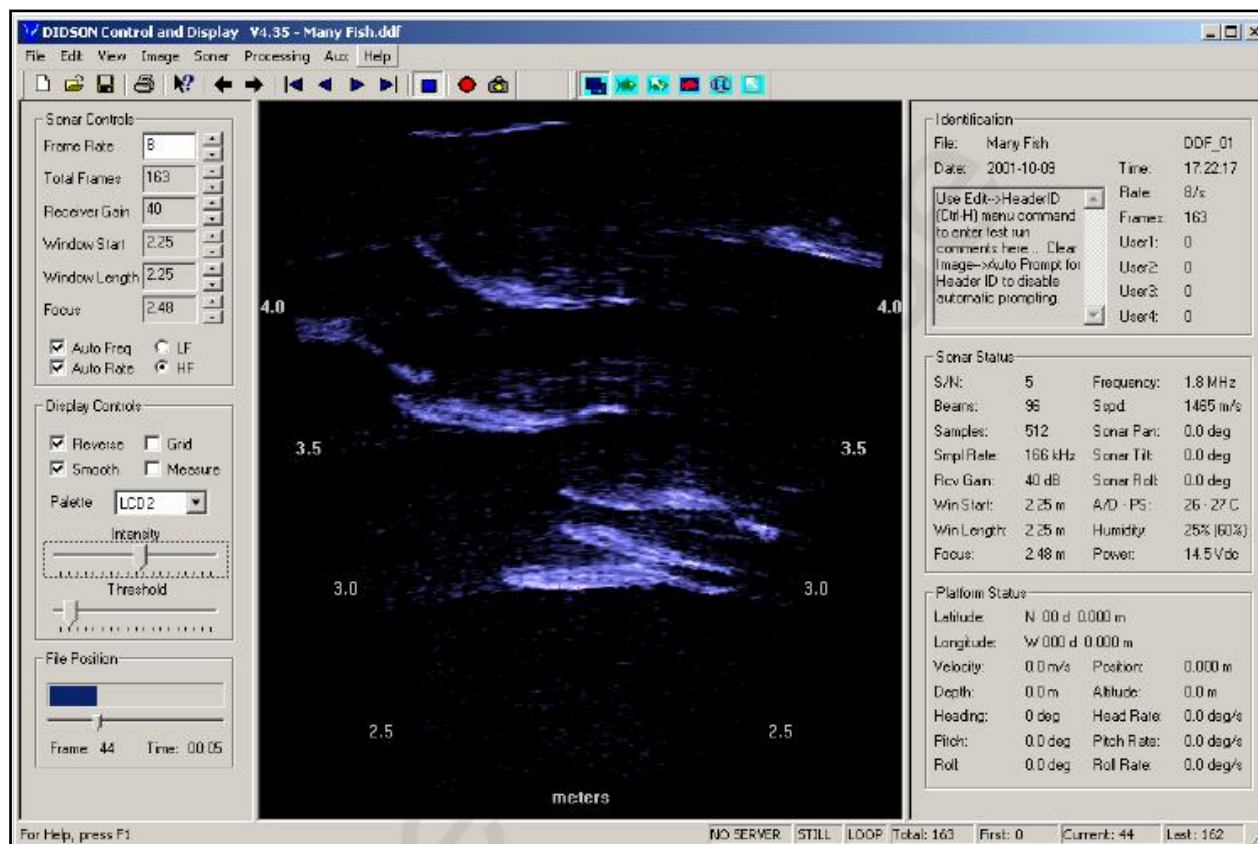

Figure 5. DIDSON screen.

Acoustical cameras are being used for underwater imaging, but they do have some shortcomings:

- Difficulty in deployment due to the higher resolution images

- Limited range due to the short wavelength transducer array

- Low signal-to-noise ratios due to the small transducer size

- Lower resolution than video images but higher resolution than sidescan or multibeam acoustical images

- Nonhomogeneity of returned signal caused by variation in angles of signals.

These shortcomings are being addressed by the mosaicking of multiple frames of data (Figure 6) and the implementation of a more automated platform (Figure 7).
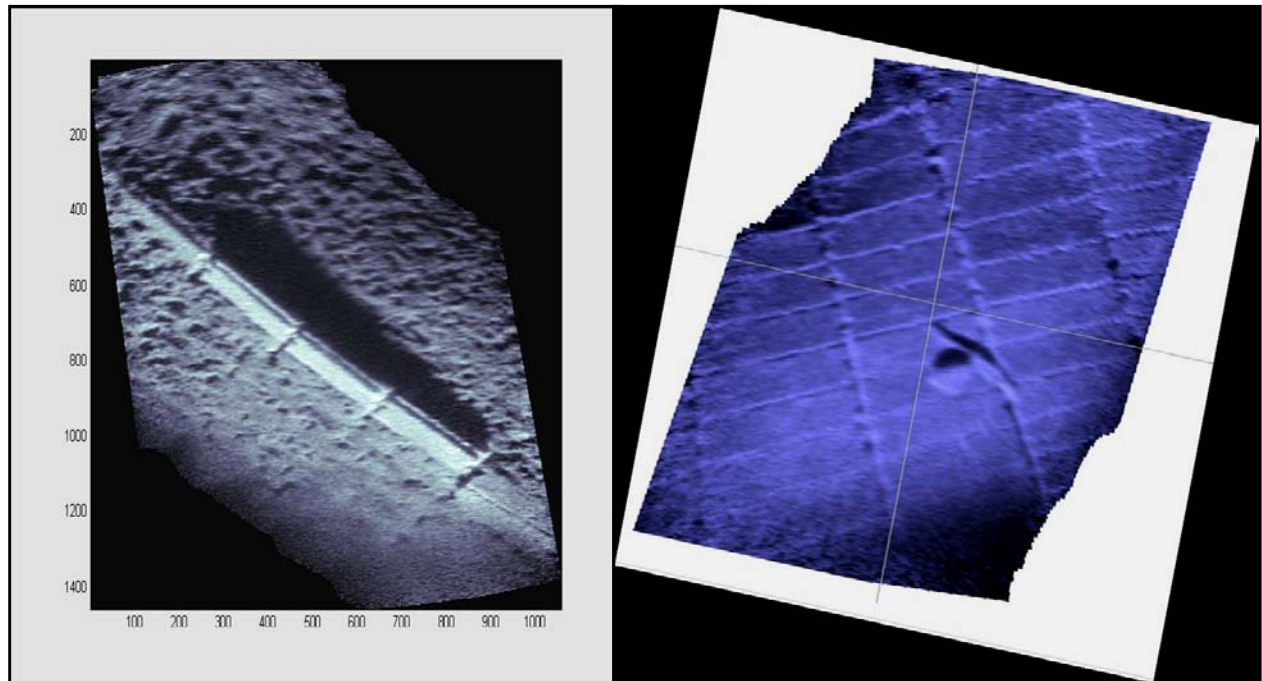
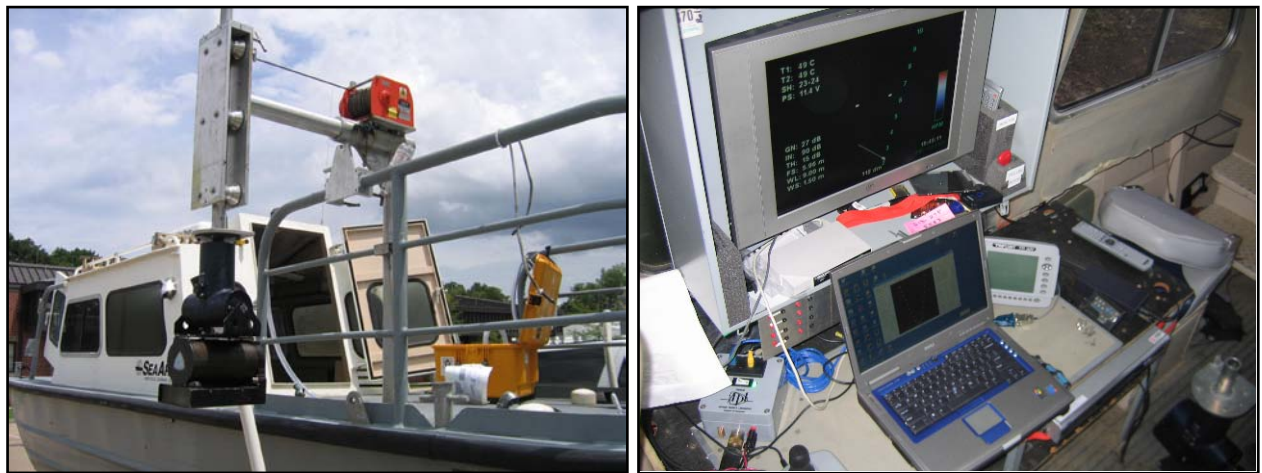Figure 6. Mosaicked acoustical images of Mississippi River Matting.

Figure 7. Automated platform for acoustical imaging.

To obtain higher resolutions than other acoustical imaging technologies such as multibeam and sidescan systems, acoustical camera systems operate at higher frequencies. This limits the range and the field of view of these instruments and requires that the acoustical camera be in close proximity to the target. In the case of the DIDSON acoustical camera, the maximum range is approximately 40 m at 1 MHz while sidescan and multibeam imaging systems operate at a much farther target distance such as 90 m (300 ft) and beyond.

To place the acoustical camera in close range of the target, several techniques of deploying the camera have been developed:

- Manually operated pole mounts affixed to lock gates, with a pan and tilt mechanism for the movement of the camera for scanning the gate

- Divers' hand-held mount for fast non-datum referenced inspection needs

- Electronically controlled pole-mounted pan and tilt mechanisms for boat-mounted GEO referenced for datum pointed referencing (see Figure 7)

- Remotely Operated Vehicle (ROV) mounted camera.

RECENT APPLICATIONS

Starved Rock Lock and Dam near Ottawa, Illinois. The acoustical imaging system was used 19 July 2006 to inspect and evaluate the degree of scouring underneath the apron leading to the stilling basin below the Starved Rock Dam. Starved Rock Dam is shown in Figure 8, and a construction drawing of the same area is shown in Figure 9. Also shown in Figure 9 is an imaging track (the coordinates of the location of the acoustical camera as it moved along the stilling basin).
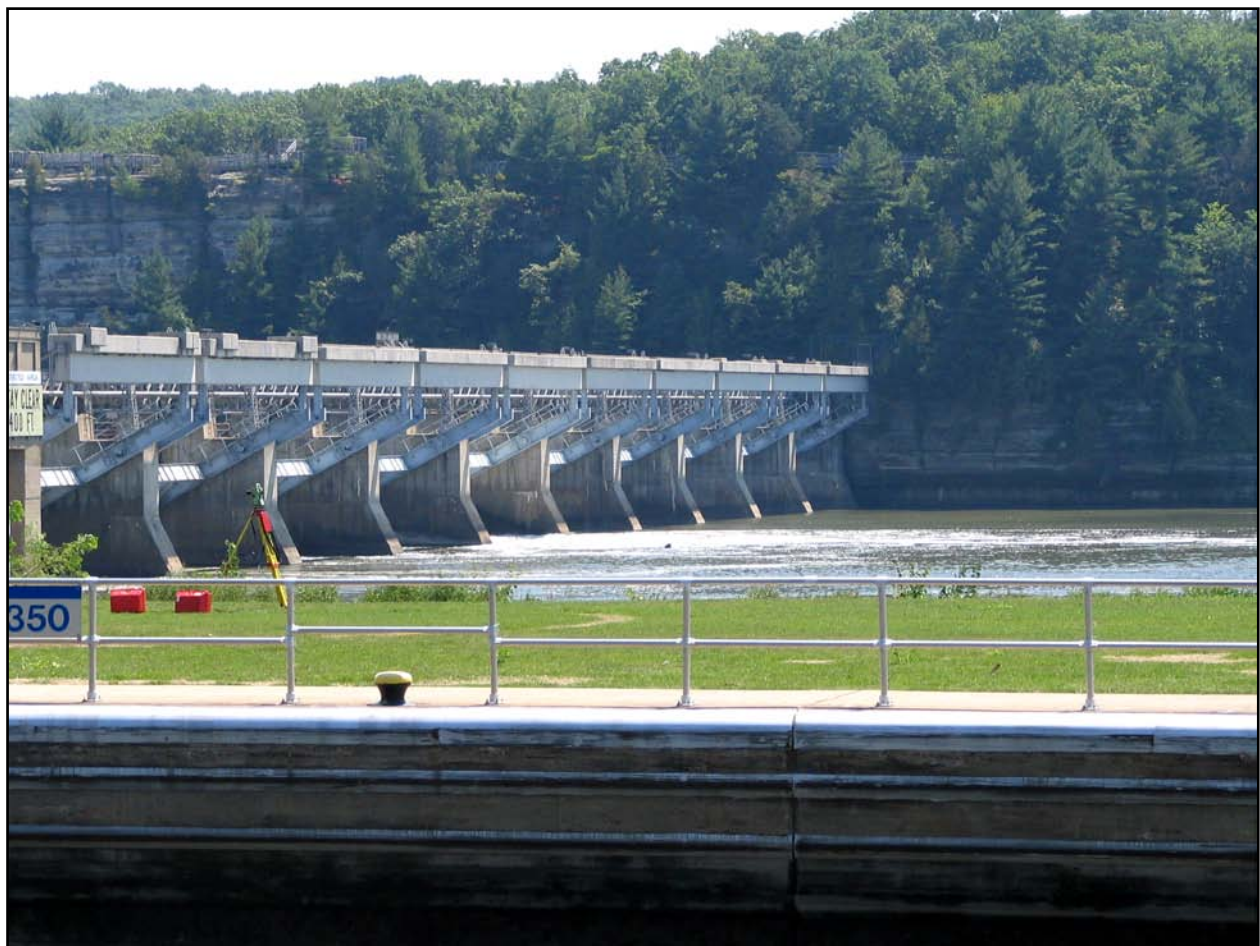

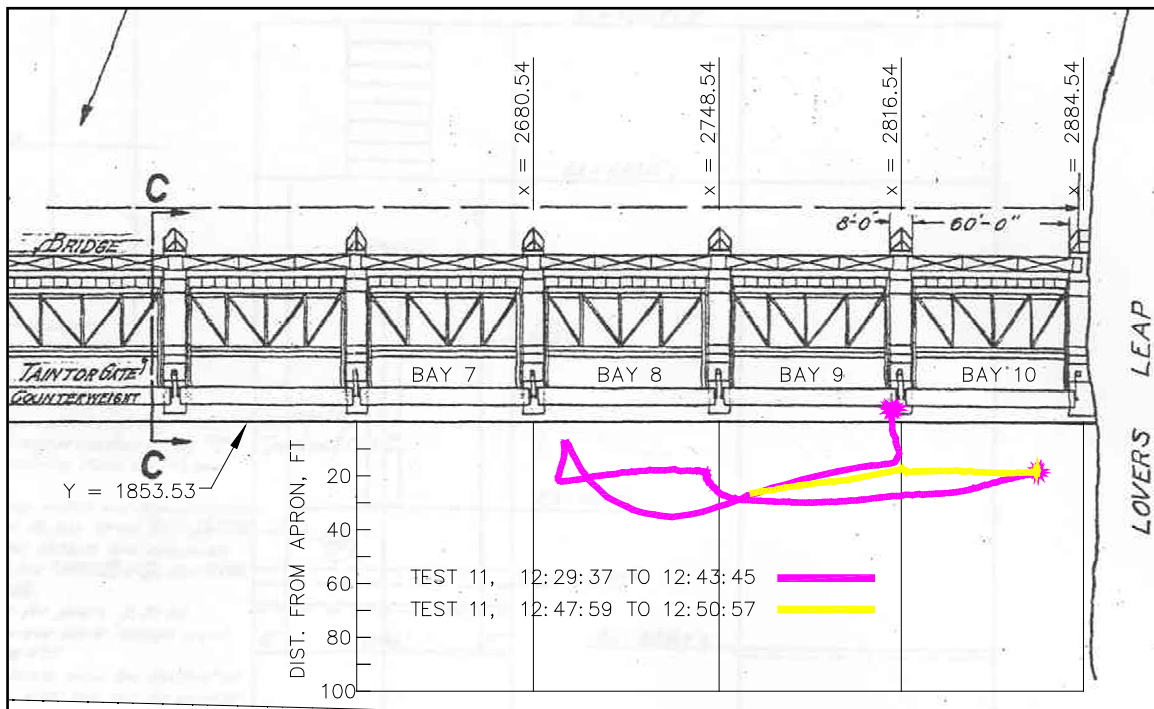Figure 8. Starved Rock Lock and Dam near Ottawa, Illinois.

Figure 9. Starved Rock Lock and Dam imaging track (1 pass).

The images obtained using the acoustical imaging system indicated that a deeper area is present downstream from gate bay 9 and about halfway into gate bay 10, and that there is no evidence of the dam apron being undermined or any significant cracking of the apron (Figure 10).
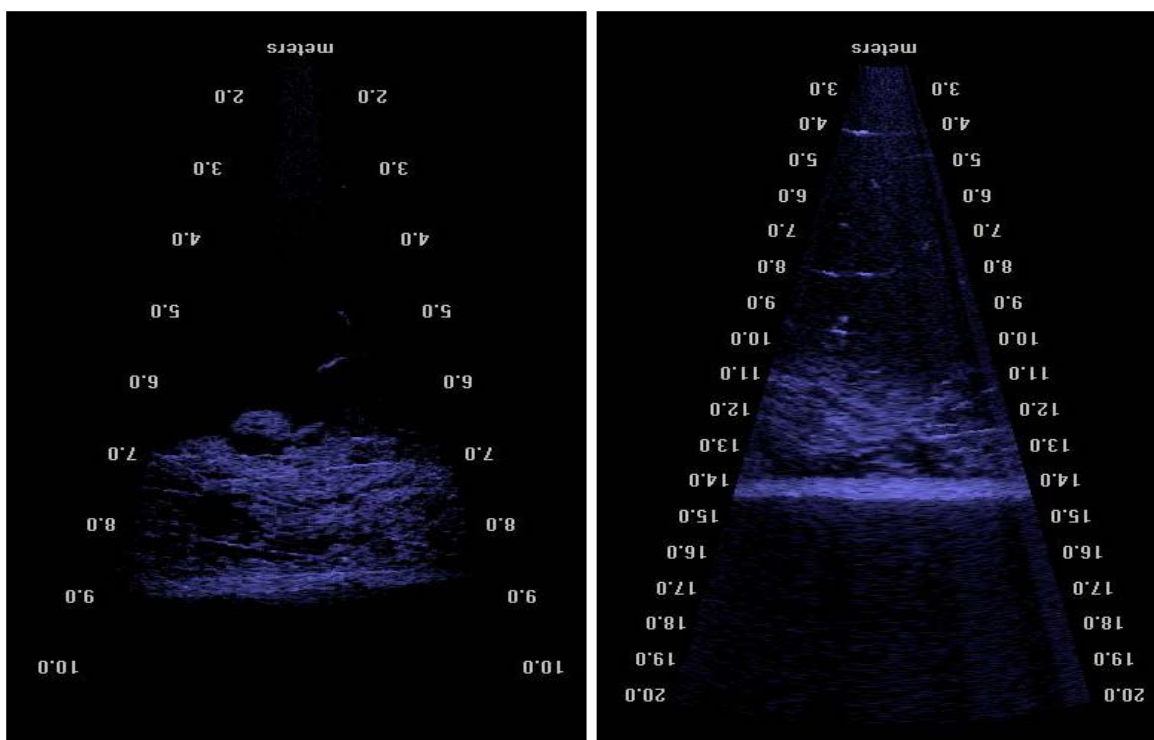

Figure 10. Acoustical images of area concerned to have scour present.

Overton Lock and Dam, near Alexandria, Louisiana. The acoustical imaging system was used 17 August 2006 to determine the amount of movement that had occurred in a section of Overton Lock and Dam on the Red River near Alexandria, Louisiana. It was believed that a portion of the dam may have moved relative to another portion.

An inspection of the interface between the two affected monoliths indicated that no significant movement had occurred. The downriver side of the dam is shown in Figure 11, and the acoustical images are shown in Figure 12. The interface between the monoliths is shown as a line in Figure 12. No appreciable elevation changes were found.

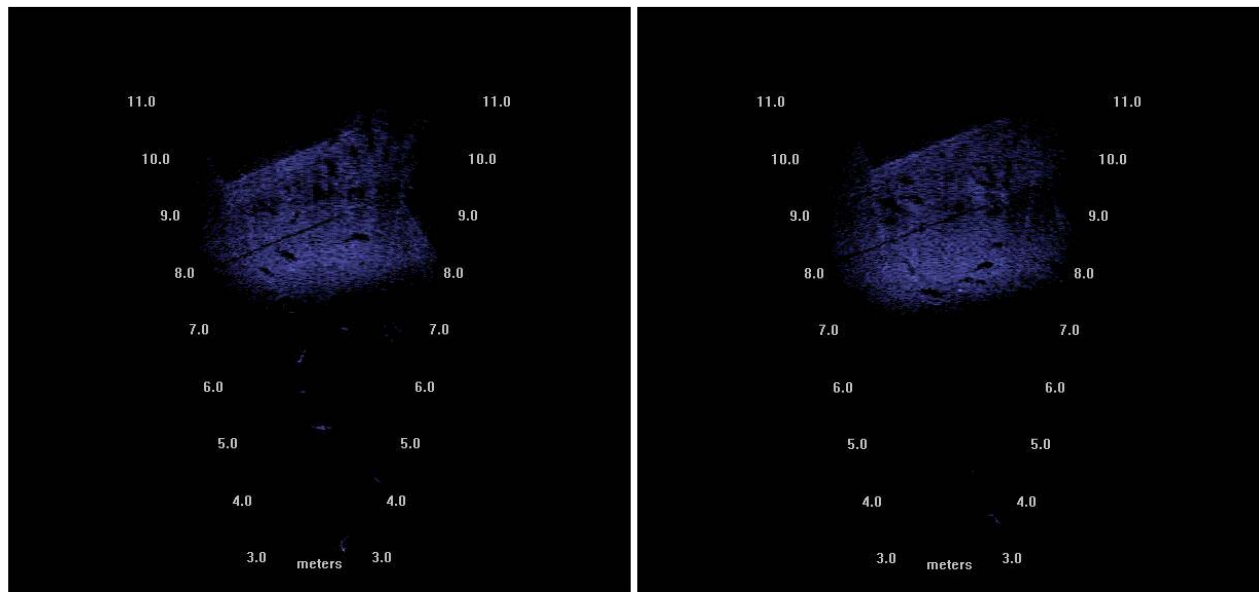Figure 11. Overton Lock and Dam down side.

Figure 12. Images of the interface of the two surfaces.

FUTURE DEVELOPMENTS IN PROGRESS: The DIDSON camera has demonstrated beneficial capabilities in the inspection of underwater hydraulic structures. Methods to improve deployment and the processing and display of data are continuing. The camera can also be mounted for use on a Remotely Operated Vehicle (ROV), which will be useful for imaging areas too dangerous for or inaccessible to divers.

Further software efforts will include the exploitation of the previously developed graphical user interface (GUI) to provide, record, and continuously display the image in the direction the camera is pointed as well as the graphical location of the target by georeferencing the data. This information will be used in any required post-processing, such as photogrammetry for three-dimensional (3-D) models. A compass has been added to the DIDSON camera along with the supporting software. This will assist in the determination of the position of the image within a given frame of reference provided by the onboard GPS system.

Scale-Invariant Feature Transforms (SIFT) or similar algorithms will be used to extract distinctive features from image data sets. The specific algorithm used will be determined by the robustness of the transform and the speed at which the computations can be made. Image data sets will be run though various filtering and enhancement algorithms to improve desired image characteristics. Researchers will work to further develop in-house capability to provide post-processing of the imaging enhancement. Shadow processing represents another possible means of extracting scene/geometry information. Just as a light source produces shadows that both reveal and mask scene information, the acoustical imaging system creates an acoustical shadow that can be processed to reveal further detail about objects and their relation to one another within the imaged region. Preliminary investigations have revealed that a tremendous gain in both image quality (bit resolution) and field-of-view is possible by proper compilation of sequential video frames. This weighted technique requires accurate translation and rotation determination and correction by sophisticated image processing methods. Integration and digitization of pan and tilt type actuators have greatly helped in this endeavor. Tracking target features through camera

movements is a major step toward the goal of 3-D model extraction by photogrammetric methods. After a 3-D model has been produced from a data set, texture maps can be overlaid on the model surfaces to produce a highly detailed and navigable representation of a scene at a fraction of the original data volume. These can be exported to Virtual Reality Modeling Language (VRML) or some other general 3-D format. Additionally, realization of photogrammetry techniques will allow 3-D measurements of scene distances to be enhanced far beyond the cross-range capabilities built into the DIDSON.

ADDITIONAL INFORMATION: This CHETN is a product of the Underwater Inspection of Navigation Structures Work Unit of the Navigation Systems Research Program (Nav Sys) being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to James A. Evans (Voice: 601-634-2535, e-mail: *James.A.Evans@usace.army.mil*). For information about the Navigation Systems Research Program (Nav Sys), please contact the Navigation Systems Research Program Manager, Charles E. Wiggins, at 601-634-4346 or at *Charles.E.Wiggins@usace.army.mil*. This CHETN should be cited as follows:

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